DOUBLE SKIN FACADE OVERALL THERMAL TRANSFER VALUE CORRECTION FACTOR IN HOT HUMID CLIMATE

OLUTOBI GBENGA AYEGBUSI

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Universiti Teknologi Malaysia

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DEDICATION

I dedicate this thesis to the Almighty God for His strength and Knowledge to complete this thesis. To my Late Father, Mr. Ayegbusi Johnson, for the good foundation you gave me. To my beloved wife, Temitope Vitoria and my daughter, Pearl Oluwasemiloore for their endless love, support, sacrifice, and encouragement.

"Thank you for all the patience and endurance."

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ABSTRACT

The ongoing discussion on the use of Naturally Ventilated Double Skin Façade (NVDSF) has been propelled by continuous advancements in building envelope design. Existing studies on NVDSF include the impacts of cavity depths, glazing types and wall types on the thermal performance of the building. However, only a few studies have focused on its cooling load, heat transferred and the building Overall Thermal Transfer Value (OTTV). Therefore, this research evaluated the impacts of the NVDSF design parameters such as window-to-wall ratio (WWR), cavity depth (CD) and glass shading coefficient (SC) on heat transfer and cooling load and developed a dataset of correction factors to calculate OTTV for buildings with NVDSF for four cardinal orientations (east, north, south and west). An experiment was carried out using a simplified 5-storey air-conditioned commercial office building with a total area of 5,760-meter square as the base-case model. Computer simulations were conducted using DesignBuilder v5.0.1.024 with EnergyPlus v8.3 simulation engine. The validation test conducted by comparing measured cavity air temperature with the simulation results showed that the software simulation is in good agreement with the measured data. Analysis of the study results revealed that naturally ventilated double skin façade was effective to minimize the solar heat gain and thermal transmittance. Proper combination of appropriate outer and inner glass panels will significantly reduce the solar heat gain as well as the resulting cooling load. The simulation model case with 0.2 m cavity depth outperformed all other tested cavity depths (0.2m, 0.4m, 0.6m and 0.8m) both in value of heat transferred and cooling loads reduction. Furthermore, the study showed that heat transmitted through both single skin façade and NVDSF will increase as window to wall ratio and the glass shading coefficient increases. The findings corroborate the fact that a carefully designed NVDSF would save a considerable amount of building energy use in hot humid climate. Based on analysis of the simulation results, the study concludes by generating a set of 8192 correction factors to calculate the OTTV of buildings with NVDSF in Malaysia. These correction factors are expected to ease the designer's burden of simulation and speed up the construction documentation process for building with NVDSF as OTTV become a compulsory requirement for construction approval in Malaysia.

ABSTRAK

Perbincangan berterusan tentang penggunaan Fasad Pengudaraan Semulajadi Dua Lapis (NVDSF) telah membawa kemajuan yang berterusan dalam reka bentuk luaran bangunan. kajian sedia ada NVDSF termasuk impak kedalaman rongga, jenis-jenis kaca yang digunakan di tingkap bangunan dan jenis dinding terhadap prestasi haba bangunan. Namun begitu, hanya beberapa kajian memberi tumpuan kepada beban pendinginan, pemindahan haba dalam bangunan dan Nilai Keseluruhan Pemindahan Haba (OTTV). Oleh itu, kajian ini menilai impak parameter reka bentuk NVDSF seperti nisbah tingkap ke dinding (WWR), kedalaman rongga (CD), dan pekali kegelapan kaca (SC) pada pemindahan haba dan, beban pendinginan, dan merangka sebuah dataset faktor-faktor pembetulan untuk mengira OTTV terhadap bangunan-bangunan yang mempunyai NVDSF dari empat penjuru orientasi kardinal. (Utara, Selatan, Timur dan Barat). Satu eksperimen telah dijalankan di sebuah bangunan komersial lima tingkat yang mempunyai penghawa dingin dengan keluasan 5,760 meter persegi sebagai model kes asas. Simulasi dalam komputer telah dijalankan dengan menggunakan aplikasi DesignBuilder v5.0.1.024 bersama enjin simulasi EnergyPlus v8.3. Ujian Pengesahan telah dijalankan melalui perbandingan suhu udara rongga bangunan yang diukur dengan hasil simulasi menunjukkan hasil simulasi dan hasil data di bangunan mempunyai keputusan yang sama. Analisis hasil kajian menunjukkan bahawa Fasad Pengudaraan Semulajadi Dua Lapis berkesan untuk mengurangkan penangkapan haba solar dan penghantaran haba dalam bangunan. Kombinasi yang sesuai antara panel kaca luaran dengan dalaman akan mengurangkan penangkapan haba solar dengan berkesan serta dapat menambahkan beban pendinginan. Model Simulasi yang mempunyai rongga yang mempunyai kedalaman 0.2 m lebih berkesan berbanding kedalaman yang lain (0.2 m, 0.4 m, 0.6 m, 0.8 m) dalam nilai penghantaran haba dan pengurangan beban pendinginan. Selain daripada itu, kajian ini menunjukkan bahawa penghantaran haba melalui fasad satu lapis dan NVDSF akan meningkat dengan meningcat nya nisbah tingkap ke dinding dan pekali kegelapan kaca. Hasil kajian ini menyokong fakta bahawa NVDSF yang direka bentuk secara teliti dapat memberi penjimatan tenaga di dalam bangunan yang berada dalam iklim panas dan lembab. Berdasarkan analisis hasil simulasi, kajian ini memberi kesimpulan dengan, menghasilkan satu set sebanyak 8192 faktor pembetulan untuk mengira OTTV bangunan yang mempunyai NVDSF di Malaysia. Dengan yang demikian, cabaran dalam mengira OTTV bangunan yang mempunyai NVDSF dapat disingkirkan walaupun indeks pengukuran untuk OTTV menjadi keperluan wajib untuk kelulusan pembinaan di Malaysia.

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LIST OF ABBREVIATIONS

ASEAN	-	Association of South East Asian Nations
ASHRAE	-	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BBRI	-	Belgium Building Research Institute
BC	-	Base Case
BES	-	Building Energy Simulation
BLAST	-	Building Loads Analysis and System Thermodynamics
CAD	-	Computer Aided Design
CD	-	Cavity Depth
CFD	-	Computation Fluid Dynamic
CF	-	Solar Correction Factor for fenestration
COP	-	Coefficient of Performance of Chiller at design point
CIBSE	-	Chartered Institution of Building Services Engineers
DB	-	DesignBuilder
DN	-	Direct Normal Radiation
DOE	-	Department of Energy (United State)
DOE.wf	-	Department of Energy weather file
DSF	-	Double skin facade
DT	-	Temperature difference between exterior and Interior design condition
ETTV	-	Envelope Thermal Transfer Value
eQUEST	-	Quick Energy Simulation Tool
GUI	-	Graphics User Interface
HVAC	-	Heating Ventilation Air Conditioner
IES-VE	-	Integrated Environmental Solutions - Virtual Environment
ICE	-	Indoor Climate Energy
LEED	-	Leadership in Energy and Environmental Design

NVDSF	-	Naturally Ventilated Double Skin Facade
MBE	-	Mean Bias Error
MMEA	-	Malaysia Ministry of Economic Affairs
MS	-	Malaysia Standard
OS	-	Open Studio
$OTTV_w$	-	Overall Thermal Transfer Value - Wall
$OTTV_1$	-	Overall Thermal Transfer Value of the orientation 1
$OTTV_{OE}$	-	Overall Thermal Transfer Value of east orientation
$OTTV_{DSF,i,j,k,l,m}$	-	Overall Thermal Transfer Value of DSF at a given orientation
OF	-	Solar Orientation Factor
RMSE	-	Root Mean Square Error
SC	-	Window overall Shading Coefficient
SC_1	-	Effective Shading Coefficient of the glass
SC_2	-	Effective Shading Coefficient of the shading device
SC_i	-	Shading Coefficient of the inner glass
SC_o	-	Shading Coefficient of the outer glass
SH	-	Horizontal Radiation
SHGC	-	Solar Heat Gain Coefficient
SSF	-	Single Skin Facade
TH	-	Global Radiation
TRY	-	Test Reference Year
UBBL	-	Uniform Building By-Law
VAV	-	Variable air volume
WWR	-	Window to Wall Ratio
WWR_i	-	Window to Wall Ratio of the inner layer of NVDSF
WWR_o	-	Window to Wall Ratio of the outer layer of NVDSF
WIS	-	Window Information System
T_{sgo}	-	Surface temperature of living wall (^{0}C)
T_{sgi}	-	Sub-Surface temperature of living wall (^{0}C)
T_{so}	-	Outside surface temperature of steel wall (^{0}C)
T_{si}	-	Internal surface temperature of steel wall (^{0}C)
T_{sco}	-	Outside surface temperature of concrete wall (^{0}C)

T_{sci}	-	Internal surface temperature of concrete wall (^0C)

LIST OF SYMBOLS

A	-	Envelope/Material Surface Area (m^2)
A_1	-	Gross area of wall at a given orientation 1 (m^2)
A_2	-	Gross area of wall at a given orientation 2 (m^2)
A_{glass}	-	Area of Window Glass
A_{frame}	-	Area of Window Frame
A_{edge}	-	Area of Window Edge
$A^{f}_{k:(1,L)}(\theta, \Phi)$	-	Directional absorptance of kth layer in system
D	-	Number of cooling degree days
E_c	-	Annual cooling energy consumption (MWh/yr) or (kWh/yr)
E_c	-	Correlation Factor
G_t	-	Incident total irradiance
Gr_L	-	Grashof Number
H_o	-	Outside air enthalpy in kg(water)/kg (dry air)
H_i	-	Inside air enthalpy in kg(water)/kg (dry air)
h_c	-	Average Convective Heat-Transfer Coefficient
I_{DS}	-	Total solar radiation received on the surface of double-skin
i	-	Incident Angle
$I_{ot,a,D}$	-	Total Direct Solar Radiation gained by the outer glass
I_D	-	Direct solar radiation
$I_{sd,a,D}$	-	Absorbed Direct Solar Radiation by the Shading Device
$I_{in,a,D}$	-	Direct solar radiation absorbed by the inner glass of double-skin
$I_{tran,D}$	-	Transmitted direct solar radiation Through double skin
$I_{ref,D}$	-	Amount of direct solar radiation reflected by the double-skin
L_{edge}	-	Length of the Window Edge
N_i	-	Absorbed solar radiation indoor flowing
N_K	-	Inward-flowing fraction of absorbed energy for kth layer
Nu_L	-	Nusselt Number

Pr_L	-	Prandtl Number based on the characteristic length L of either the plate
Q	-	Total heat transfer through the building envelope
Q_c	-	Conductive Heat Flow (W)
Q_v	-	Ventilation air flow in L/s
Q_w	-	Conduction heat gain by wall
Q_g	-	Conduction heat gain by window
Q_s	-	Solar gain heat gain by window
$^{Annual}Q$	-	Annual heat gain
Ra	-	Reynolds Number
Re_L	-	Rayleigh Number
R^2	-	Coefficient of Determination
$T_{dir\text{-}sol}$	-	Direct Solar Transmittance
T_i	-	Design indoor air temperature 21,^{0}C
T_c	-	Concrete roof surface temperature, ^{0}C
T_{ai}	-	Design indoor air temperature 21^{0}C,
T_{ao}	-	Monthly mean outdoor temperature (^{0}C)
T	-	Air gap temperature due to living wall system (^{0}C)
T_g	-	Temperature of the Green roof surface (^{0}C) measured from the set up
T_o	-	Exterior/Outside Temperature
T_i	-	Indoor/Inside Temperature
T_∞	-	Temperature of fluid away from surface
T_s	-	Surface Temperature
t_o	-	Outside temperature (^{o}C)
t_i	-	Inside temperature (^{o}C)
TD_{eq},	-	Equivalent temperature difference (^{0}C) for opaque wall
T_{sc}	-	Total shading coefficient due to window glass and deciduous plants in front of window
$_\Delta$T	-	Temperature difference between outdoor and indoor condition for window (^{0}C)
$T_{1,L}^{fH}(\theta, \Phi)$	-	Directional-hemispherical front transmittance of system

T_{R1}^4 & T_{R2}^4	-	Absolute Temperature of the two surfaces in Stefan-Boltzmann law
U_{glass}	-	Thermal Transmittance of Window Glass Component
U_{frame}	-	Thermal Transmittance of Window Frame
U-value	-	Thermal Conductivities
U_{win}	-	Thermal conductivity value of window (W/m^2 K)
U_w	-	Thermal transmittance of wall (W/m^{2}K)
U_f	-	Thermal transmittance of fenestration (W/m^2 K)
U_l	-	U value of living wall (W/m^{2}K)
U_a	-	Thermal transmittance of air gap (W/m^2 K)
U_g	-	U value of Green roof
U_r	-	Thermal conductivity value of roof (W/m^2 K)
U_t	-	Total heat transfer coefficient of Green roof (U_g) and concrete roof (U_c)
W	-	Watt
W_o	-	Outside humidity in kg(water)/kg (dry air)
W_i	-	Inside humidity in kg(water)/kg (dry air)
α	-	Absorption coefficient of wall due to solar radiation
α_s	-	Solar absorptance of the single pane of glass
$\bar{\alpha}_{ot,D}$	-	Absorption Rate of the Outer Glass in double skin facade
$\bar{\alpha}_{sd,D}$	-	Absorption Rate of the shading device in double skin facade
α_{sd}	-	Shading device absorption rate
$\bar{\alpha}_{in,D}$	-	Absorption rate of the direct solar radiation at the inner glass surface
ρ	-	Reflectance of incident radiation
ρ_{gr}	-	Ground reflectance
$\bar{\rho}_D$	-	Reflection rate of direct solar radiation
ρ_{sd}	-	Reflectance rate of the shading device
$\rho_{in,D}$	-	Inner Glass Reflectance of the direct solar radiation
$\rho_{ot,D}$	-	Outer Glass Reflectance of the direct solar radiation
γ	-	Linear function or correlation function for design space cooling load

ρ_a	-	Density of air = 1.28 kg/m^3= P/RT$_a$, Atmospheric pressure 100 KPa, R= 287 J/kg K
ψ_{edge}	-	Linear Heat Transmittance Coefficient
θ	-	Incident angle relative to normal layer
Φ	-	azimuthal angle (in plane of layer, about normal)
N_K	-	Inward-flowing fraction of absorbed energy for kth layer
$\tau_{ot,D}$	-	Transmission of the solar radiation at the outer glass
$\tau_{in,D}$	-	Transmission rate of direct solar radiation through the inner glass
$\bar{\tau}_D$	-	Direct solar radiation rate of transmittance
u	-	Velocity of wind 2.8 m/sec
σ	-	Stefan-Boltzmann constant (5.67 x 10^{-8} W m^{2}K^4)
ε	-	Surface emissivity for long wave thermal radiation varies from (0.9 to 0.95)
$\sum H_w$	-	Summation of annual heat gain by wall for 8760 hours a year
$\sum H_g$	-	Summation of annual heat gain by window for 8760 hours a year
$\sum H_s$	-	Summation of annual solar heat gain by window for 8760 hours a year
$\sum_{n=Dec.}^{Jan} Q_{a,b,c,d,e,f}$	-	Heat gain through the building facades on four different orientations over the period of a year

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CHAPTER 1

INTRODUCTION

1.1 Introduction

This thesis focuses on exploring the potential and application of Naturally Ventilated Double Skin Façade (NVDSF) in Malaysian building industry, to improve the commercial building energy consumption by reducing the Overall Thermal Transfer Value (OTTV). This Chapter presents the research background, problem statement, research gap, questions, objectives, scope, limitation, significance and the structure of the study.

1.2 Research Background

The primary goal of building from human history has been to protect man from weather element. The building envelope, comprising of the facade and the roof are the elements that shields the indoor space from the outside climatic conditions (Straube, 2006a) and (Straube, 2006b). However, the conventional understanding of building envelope performance keeps changing as the construction materials and method changes due to advancement of technology and innovation. The inherent functional requirements of a building envelope are becoming more elaborate, from simply being durable and able to control climatic elements to other requirements that include, energy efficiency, carbon footprint control, fire safety and thermal comfort capacity (Kesik, 2016). Building envelope is therefore the building component with solar heat management role, providing the necessary cooling and heating control without compromising the required aesthetics (Sadineni, Madala, Boehm, 2011). Balancing this condition is crucial for efficient functioning and performance of the building.

The emergence of modern architecture brought about a rapid increase in high rise buildings with glass façade. Both the postmodern and international architectural style are mostly characterized by the glass façade envelope which comes with its related cooling and heating energy issues – heat loss during the winter and solar gain during the summer, though it provides not only a good aesthetic view but also offer occupants an opportunity to take advantage of exterior views and potential natural ventilation (Elkadi, 2006). With this emerging building energy-use reduction as a major concern, the search for better approach to improve the energy efficiency of buildings has intensified (Hien *et al*, 2005; Santamouris, 2010). As a result, building design strategies to improve the energy performance using different shading designs, such as overhangs (Ossen, 2005; Lee and Tavil, 2007) and venetian blind (Simmler and Binder, 2008).

Also, responsive facade technologies have been developed for high-end office buildings (Wigginton, 2002) in which the designers integrate additional building services into the facade system. By using building envelope systems can interact with the environment thereby reduce the amount of supplementary heating or cooling needed to maintain the indoor comfort (Azarbayjani, 2002). Different façade designs have demonstrably shown to vary in its performance with respect to their location. For example, the facade design requirements of building in tropical climate compared to buildings in cold and temperate climate differ significantly. As envelope designs of many commercial buildings in Malaysia follow the lead of modern architecture style on full glass facade which potentially lead to high energy use to provide a comfortable indoor environment, design strategies such as external or internal shading devices, Double Skin Facade (DSF) have been considered to be a better alternative (Baharvand *et al*., 2012; Sánchez *et al*., 2017; Aziiz *et al*., 2018).

Architects have adopted DSF for different purposes ranging from aesthetics, thermal comfort enhancement, acoustic insulation purpose, fire insulation and indoor light enhancement in some cases (Alavedra *et al*., 2003, Chow, 2013, Gavan *et al*., 2010). Figure 1.1 summarises a number of user’s requirements for DSF adapted from different existing studies. Kalyanova (2008) and Ghaffarianhoseini *et al*. (2016) among many others also identified various advantages of DSF and its structure for building performance. The 1.2 m ventilated double-glazed facade incorporated on the Securities Commission building in Malaysia is designed for multipurpose function that include walkaway space, maintenance purpose and acoustic buffer zone (Xin and Rao, 2013).

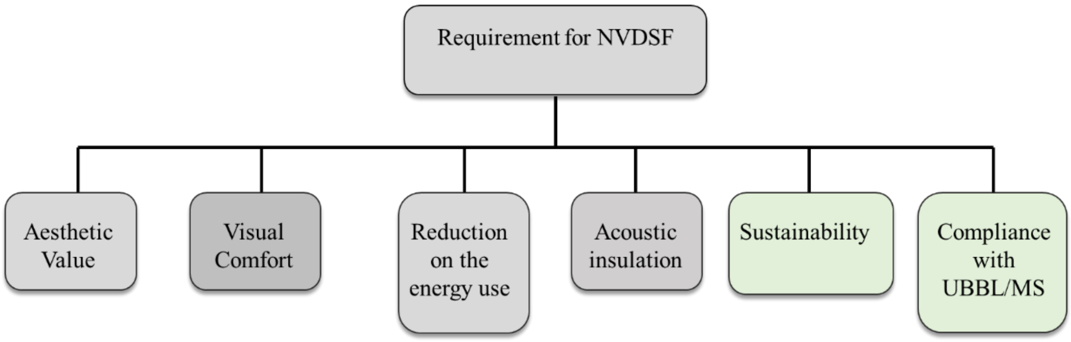

Figure 1.1 User's requirements for NVDSF

The concept of DSF system has been explored by many authors (Poirazis, 2004). Saelens (2002) defines DSF on the basis of the envelope's construction, the transparency of the façade surfaces and the cavity airflow. Parra *et al*. (2015) in another study defines DSF as *"a building typology consisting of two skins (a glazed outer layer and either a glazed or mixed inner layer) placed in such a way that air flows in the intermediate cavity. The cavity air ventilation (either natural or mechanical) is used for evacuating the radiative heat absorbed by the façade elements. The outer glazed skin can be single glazing or double glazing units with a distance from 20 cm up to 2 m from the inner skin. Sometimes, for radiation protection, solar shading devices are placed inside the cavity''*. Both mechanically ventilated DSF (Aleksandrowicz and Yezioro, 2018) and naturally ventilated DSF (Sánchez *et al*., 2017) have been tested to perform well in warm or hot climate. Not only has ventilated double skin façade been studied in the tropical climate like Malaysia and Indonesia (Mulyadi, 2012; Baharvand *et al*., 2012; Rahmani *et al*., 2012), its application on the Securities Commission building and the recently completed Suasana PjH (Putrajaya Lot 2C5) indeed shows that NVDSF is becoming popular in Malaysia.

Similarly, Overall Thermal Transfer Value (OTTV) was adopted as a voluntary measuring index to evaluate facade's annual thermal performance with respect to its solar heat transmission (Malaysia Standard 1525). The tool has since its adoption undergone series of reviews (Kannan, 1991; Deringer & Busch, 1992 and MS 1525:2007). Selangor Uniform Building Amendment (No. 2) By-Laws 2012 states the provision for OTTV and Leong (2017) discussed incorporation of OTTV in the Uniform Building By-Law (UBBL) for necessary enforcement. The UBBL amendment under consideration stipulates that a ‘‘*new or renovated non-residential buildings with air-conditioned space exceeding 4,000 square metres shall be designed to meet the requirements of MS 1525 with regards to OTTV (50 W/m^2) and the roof thermal transfer value”* (Malaysia, 1984; Selangor Uniform Building (Amendment) (No. 2) By-Laws 2012; Leong, 2017). This is to ensure that non-residential building with air-conditioned spaces adhere to this standard by reducing its environmental impact, the results of which aligns with the eleventh Malaysian eleventh plan on pursuing green growth for sustainability and resilience in Malaysia (M.M.E.A., 2015).

Awawdeh and Tweed (2014) explained that the performance of a building envelope system can be assessed by either adopting a performance-based evaluation tool which provides systematic evaluation approach or by comparing the performance of the building under consideration to that of a standard building using key performance indicators such as annual energy consumption of the buildings per floor area. The assessment can be achieved by comparing the building to a target value which represents the maximum energy budget building. However, in the context of the present study the existing performance base method – OTTV is applicable in Malaysia.

1.3 The Problem Statement

Previous studies on surveys and building energy audits of office buildings in Malaysia showed a more than 40% carbon gases contribution to the overall greenhouse gas (Zakaria *et al.*, 2012; Hassan *et al.*, 2014), most of which is as a result of high energy use due to cooling load. Therefore, the works of Ossen (2005), Xin and Rao (2013), Lau *et al. (*2016) and Ariffin (2016) represent examples of a continuous exploration of different architectural design strategies to mitigate emissions from buildings by reducing its energy use and ensure thermal efficiency. Similarly, the studies of Baharvand *et al*. (2012) and Rahmani *et al*. (2012) on DSF supports the claim that NVDSF can substantially reduce cooling load and improve building thermal performance.

However, considering all the parameters in the existing Malaysian OTTV formula which include the window-to-wall ratio (WWR), transmittance of wall (U_w), and fenestrations (U_f), shading coefficient (SC), solar factor (SF), wall absorption (α), the coefficient of temperature deference between wall (ΔT) and fenestration (DT), an extra parameter is introduced by the stack effect created in the cavity of a naturally ventilated double facade system. Oladokun (2015) of Green Earth Solution (GEDS) Sdn. Bhd confirmed the challenge to calculate OTTV for building with DSF during a Green Building Index Facilitator's training in Kuala Lumpur. Also, one of the site Architects of the newly completed Suasana PjH complex raised similar issue during a site visit, stating that existing Malaysian OTTV formula (Equation 1.0) fall short to accurately calculate OTTV for building with NVDSF (Mohammed, 2017). Figure 1.2 illustrates an example of a fully glassed hypothetical building exposed to both direct and indirect solar radiation with potential of high OTTV. The impact of the parameter introduced by the cavity stack effect is illustrated in the next section.

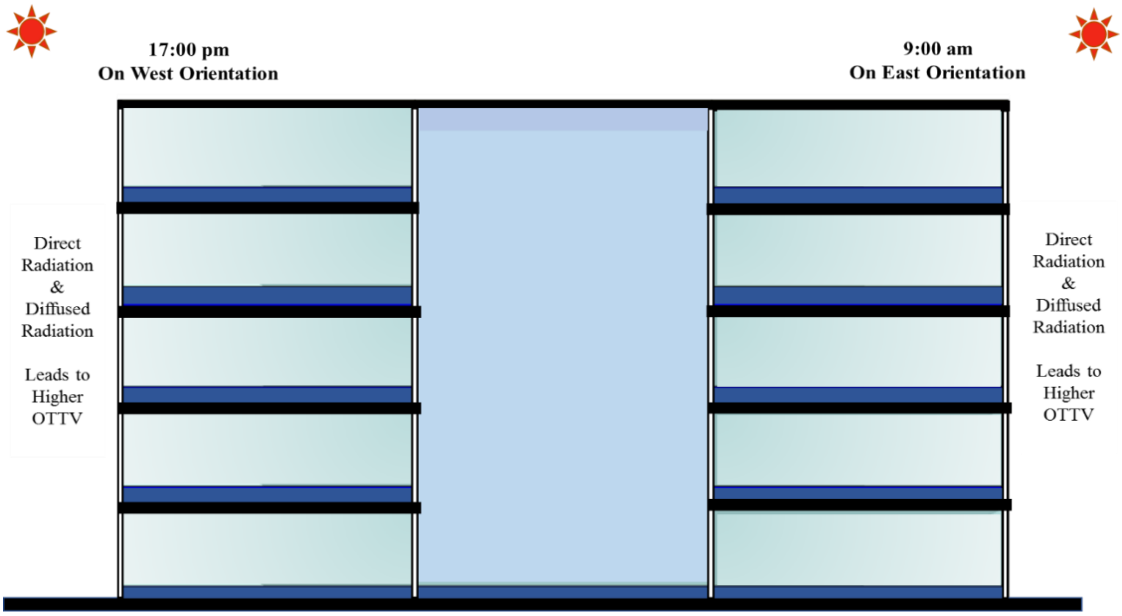

Figure 1.2 The need for NVDSF: Hypothetical fully glazed office building with impact of direct sunlight.

1.4 Research Hypothesis

From existing theory and reviews, NVDSF provides sun shading from both direct and diffused solar radiation which in turn helps to reduce the transmitted solar heat gain into the building. The stack effect illustrated in Figure 1.3 introduces another parameter into the situation compared to the scenario presented in Figure 1.2. This additional parameter is potentially missing in the existing Malaysian OTTV formula. Therefore, the hypothesis of this thesis is that calculating OTTV for building incorporated with ventilated double skin façade will require a Correction Factor (CF) to multiply the existing formula given in the Malaysia Standard (MS 1525: 2014) as shown in Equation 1.1 (Chan & Chow, 2013).

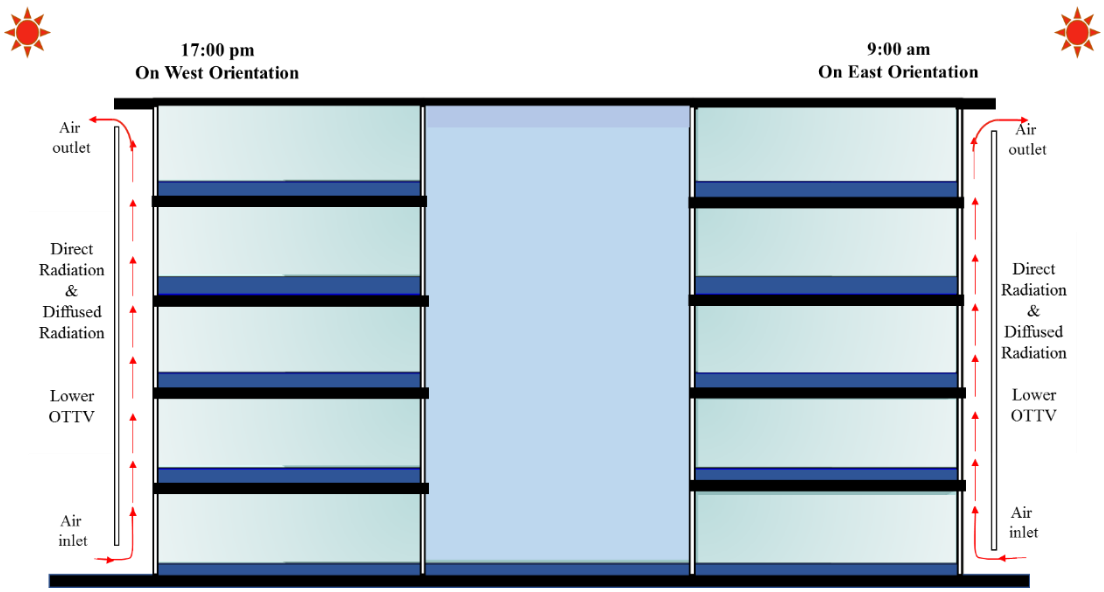

Figure 1.3 The research problem: Hypothetical office with NVDSF and the challenge to calculate OTTV.

$$OTTV_W = 15\alpha(1 - WWR)U_W + 6(WWR)U_f + (194 * \mathrm{WWR} * \mathrm{SC}) \qquad (1.0)$$

$$OTTV_{DSF} = [15\alpha(1 - WWR)U_W + 6(WWR)U_f + (194 * \mathrm{WWR} * \mathrm{SC})]X \qquad (1.1)$$

The function '*X*' in equation 1.1 represents the impact of the constant air-flow through the cavity of the NVDSF. This correction factor multiplied with the result from OTTV of Single Skin Façade (SSF) calculates the corresponding OTTV for building incorporated with NVDSF (Chan & Chow, 2013).

1.5 The Research Questions

The leading assumption in this study as discussions about the application and efficiency of NVDSF in Malaysia context grow among researchers is that thermal performance of buildings with NVDSF would be better than that with SSF. However, it is important to consider the challenge of calculating the OTTV being one of the building design submission requirements by authority. Therefore, the main research question can be posed as follows:

Is the existing OTTV formula given in the MS 1525:2014 suitable for buildings incorporated with NVDSF? The following driving questions will be addressed to provide an answer to the main question:

i. What are the parameters required for calculating building OTTV?

ii. What is the impact of window-to-wall ratio (WWR) on transmitted solar heat gain and OTTV of a building with NVDSF?

iii. What is the impact of shading coefficient (SC) on OTTV of a building with NVDSF?

iv. How does the air-flow through the cavity of a NVDSF impact the solar transmission on cardinal orientation?

v. What is/are the correction factor(s) required to calculate the OTTV for commercial buildings with NVDSF in hot-humid climate?

1.6 The Research Gap

Table 1.1 below presents the summary of the some of the literature review that are related to this present study. These studies include evaluating the performance and optimization of various envelop design elements of DSF to either achieve a lower energy use, enhance indoor ventilation or to evaluate the OTTV of other of façade design. However, only few researchers discussed OTTV of a double skin façade.

Literature review shows that there are many studies on the potential of different kinds of DSF and their advantages (Poirazis, 2004, Gratia, and De Herde, 2007). The design and construction of the Securities Commission building with a 1.2m cavity in Malaysia marked the early adoption of DSF in the Country and provided grounds for more studies on the viability of the façade system. However, the studies submitted by both Rahmani (2012) and Baharvand (2012) only go so far to consider the indoor air temperature of an office and classroom attached to a ventilated DSF respectively, but no explicit work on DSF's impact on both cooling loads and Overall Thermal Transfer Value.

Similarly, the study conducted by Nikpour *et al*. (2012) on overall thermal transfer value focused on the impact of self-shading on solar heat transmission through the façade by evaluating the building OTTV in Malaysia. Yet, they do not cover the impact of a ventilated second skin and its various design parameters on the resulting OTTV.

The study presented by Chan and Chow (2014) covered the OTTV calculation of building with DSF where a series of correction factors were developed. This study provided the necessary insight for the present study although the solution it provides is not applicable in Malaysia because of climate differences. For instance, Hong Kong has four seasons and the use of air conditioner runs from April through October unlike in Malaysia. Also, the Hong Kong version of overall thermal transfer value considers only the solar radiation through fenestration and the conduction through opaque wall while the conduction through fenestration is considered insignificant. Whereas, the Malaysian OTTV version adequately considers all forms of solar transmission (conductive and radiative) through facade components. Therefore, this thesis attempts to focus on the making OTTV calculation of building integrated with NVDSF easier in Malaysia and the general concept employed in the present study will not only be applicable in Malaysia but would also be useful for similar climatic hot and humid regions.

Table 1.1 Summary of previous researches related to DSF, building energy use and OTTV

Researcher(s)	Climatic Zone	Objective (Parameters)	Methodology	Result/limitation
Pomponi, Barbosa and Piroozfar (2017)	Cold and Humid; warm and humid	To compare the possible thermal comfort in building model with a DSF in cold and warm climates.	IES-VE and CFD was used to determine & assess indoor thermal conditions.	The results from this study indicate that careful design of DSF can enhance natural ventilation, reduce energy demand and CO_2 emission.
Andelković *et al.*, (2014)	Temperate	The study was designed to investigate natural ventilation potential in a multi-storey naturally ventilated DSF.	Measured data from an experimental setup on the NE orientation	The results show that a double skin facade does not necessarily reduce energy consumption except when it is carefully designed.
Chan & Chow (2013)	Sub-Tropical	Calculation of the Overall Thermal Transfer Value of building with green roof	Data from an existing building case was collected for energy simulation validation purpose	Overall Thermal Transfer Value formula for building with green roof is developed. However, the researcher noted that the results viability should be verified in another climate.
Joe *et al.* (2013)	Temperate	To evaluate the performance of a multi-storey building integrated with DSF system	The researcher compared measured data from the target building to parametric simulation results	The simulation data showed a 15.8% and 7.2% reduction of in cooling and heating loads respectively
Hamza (2008)	Hot arid climate	To Compare the performance of a SSF building with DSF system	The methodology involves simulation of a generic building space with an Air-conditioner.	The result indicates that a reflective glass in a double skin facade system outperforms a single skin façade with reflective glass in arid climate context.
Baharvand *et al.*, (2012)	Hot and Humid	To examine the integration of DSF and solar chimney to enhance internal air velocity.	DesignBuilder CFD was used to simulate the natural ventilation of selected classroom	Provides possibility to enhance internal natural ventilation with integration of DSF and solar chimney if proper optimizations have been implemented.
Rahmani et al. (2012)	Hot and Humid	To determine the impact of different cavity depths on indoor air temperature of building with DSF.	Flovent CFD simulation of air-conditioned building used in the study.	Increasing the cavity size up to one meter reduces solar heat gains in the building, the DSF has its efficiency reduced, overheating and cost.
Nikpour *et al.* (2012)	Hot and humid	To evaluate the OTTV of self-shaded building in Malaysia context, in relation to the building energy use.	Experimental and analytical approaches	The result shows that self-shaded building results in a much lower OTTV and hence lower energy building use.
Vijayalaxmi (2010)	Varies: temperate, Hot and Humid	To review the Overall Thermal Transfer Value concept and discuss both the significant and limitations	Calculation of Overall Thermal Transfer Value of chosen building case.	The research observed that overall thermal transfer value must be defined in reference to the local context to avoid errors. Also, the study suggests that Overall Thermal Transfer Value should be considered at pre-design stage for better efficiency and application.

1.7 The Research Objectives

The goal of the research is to dive deeper into the ongoing discussion about the application of NVDSF in Malaysia by assessing and evaluating the impact of the ventilated double skin façade in reducing the solar heat transmission into the building. Thereby develop a set of correction factor for calculating the OTTV of buildings incorporated with NVDSF in Malaysia.

Other specific objectives of the study are as follows:

i. To determine the important parameters for calculating OTTV of conventional façade.

ii. To evaluate the impact of window-to-wall ratio (WWR) on transmitted solar heat and OTTV of a NVDSF.

iii. To evaluate the impact of shading coefficient (SC) on OTTV of a NVDSF model.

iv. To evaluate the effect of air flow through the cavity of NVDSF on solar transmission on cardinal orientation.

v. To develop a series of correction factor to calculate OTTV of Malaysian commercial building integrated with NVDSF.

1.8 The Research Scope and Limitation

Most of the reviewed literature point out many justifiable reasons for DSF application in Malaysian context with respect to its thermal comfort and performance potential (Ramani, 2012 and Bahavard, 2013). The recently completed Suasana PJH (Putrajaya Lot 2C5) complex and the envelope design features affirms that. Therefore, it is crucial to ease the OTTV calculation process for this kind of facade design for designers to meet the present-day design documentation requirement. This research scope focuses on the impact of cavity air flow on OTTV of building incorporated with NVDSF under Malaysia climate context.

The thermal performance evaluation and analysis in this study focus on the amount of solar heat transmitted through two types of building facades: the single skin facade and NVDSF. While there are many variables that could impact the solar heat transmission through the components of either SSF and NVDSF, this research analysis is limited to the impact of window-to-wall ratio, the glazing material's shading coefficient and the incorporated cavity depths on four orientations (East, West, North and South) of the building model.

Apart from the solar heat transmission, the impact of air flow through the cavity of NVDSF on cooling load and the corresponding OTTV is also evaluated using the chosen simulation tool by comparing the results. However, the air temperature, humidity as it relates to occupants' thermal comfort in the office spaces is not dealt with in this thesis. The mechanical operating system remains constant in all the tested cases for both daily and annual simulations. The working schedule for the office is considered from 9.00 hour to 17.00 hour.

A simple generic open-plan office model was selected for the experiment to capture the solar transmission through the façade of different orientations. The energy and OTTV analysis of NVDSF case is performed and discussed in reference to that of the base case. The base case is designed to replicate the model used by Kannan (1991) in the development of existing OTTV formula as much as possible. These assumptions are adopted to simplify the calculation process.

1.9 Significance of Study

The goal of this study is to demonstrate the effect of ventilated double skin façade with respect to lowering the building cooling load and reducing the calculated OTTV. The study is also expected to produce a database of correction factors from which professionals designing buildings with NVDSF can select for easy calculation of the OTTV as required in Malaysian Standard (MS 1525:2014; Selangor Uniform Building (Amendment) (No. 2) By-Laws 2012; Leong, 2017).

Furthermore, this study is expected to add to existing body of knowledge on the subject both locally and beyond. The research results will provide additional value to existing building design standard in Malaysia as it relates to building integrated with NVDSF. Achieving this goal would contribute towards achieving the sustainable development aspect of the eleventh Malaysian plan which includes providing sustainable buildings with minimal impact possible on the environment (MMEA, 2015). Finally, this research output is expected to be of value to building authorities that is responsible to either develop or improve existing building energy standards for better energy efficiency as well as to other construction professionals who are responsible for submitting construction documents to approving authority.

1.10 Thesis Structure

The thesis is structured into six chapters and the summary is given below:

Chapter one presents the background issues of this research which includes: the research problem statement, the research gap, research objectives and questions, the identified research hypothesis. Also, the chapter discuss the scope and limitations to the study. The Chapter conclude with the significant of study and the overall structure of the thesis.

Chapter two is divided into four sections that generally explore the issues around building envelope thermal performance and the evaluations. Section one reviews the evolution of building envelope and how its functional requirements have changed over the years. Also, the Double Skin Façade background, its classifications based on cavity ventilation mode and the cavity partitioning are reviewed. In section two, the principle of heat transfer through envelope components and how the physical properties of these components affect the envelope overall thermal performance is reviewed. Section two also presents a quick review mode of heat gain in building that may impact building cooling load. With focus on NVDSF and its thermal performance, a quick review of previous studies on NVDSF is also presented to identify façade parameters that researchers have considered important. An extensive review of different methods employed by researchers to evaluate thermal performance of NVDSF is presented in section three. In section four, a review of commercial building energy standards is presented, with focus on Malaysian standard to understand the state-of-the-art on overall thermal transfer value.

Chapter three is designed to describe the research methodology for this study. Therefore, the first section presents the process and validation result of the chosen simulation tool (DesignBuilder) identified in Chapter two. The statistical tool selected for the validation is also discussed. Models employed in existing studies are presented leading to the definition and development of a simplified commercial building Base Case (BC) with NVDSF model cases. Also, section three presents the characteristics and the simulation assumptions employed in this study along with the construction materials and thermo-physical properties for the chosen model. DesignBuilder (DB) simulation procedure, the software setup and the results analysis criteria are finally presented in section four of this Chapter.

Chapter four presents the results and analysis of daily solar heat transmitted through the model facades. Also, the impact of incorporated ventilated cavity on the base case daily solar heat gain is evaluated and presented from the data obtained from NVDSF model daily simulation. The following simulation results are analysed:

1. The impact of window-to-wall ratio on daily solar transmission through the building façade,

2. The impact of shading coefficient on daily solar transmission through the building façade,

3. The impact of NVDSF on daily solar transmission through the facade system into the building.

4. The relationship between cavity depth and the daily solar heat transmitted through NVDSF.

Chapter five presents the annual simulation results of both base case and NVDSF models with focus on identified parameters to achieve the main objectives of this thesis. This Chapter is presented in four sections: section one presents the annual heat transmission, the cooling load and the OTTV of building with conventional facades. The results of the correlation study that would help to understand the relationship between the amount of annual heat transfer through the facade and the corresponding OTTV is presented in section two. The effect of ventilated cavity on annual cooling load of models with NVDSF on the cardinal orientations is presented in section three. Finally, section four discusses the correction factors (CF) developed, the validation result of the CF and conclude with how these factors can be used to calculate the needed OTTV for building with NVDSF. In summary, the following parameters is evaluated:

1. The effect of different window-to-wall ratio on annual heat gain and cooling load,

2. The effect of glass shading coefficient on both annual cooling load and solar transmission,

3. The effect of ventilated cavity on both annual solar heat gain and cooling load, and

4. The relationship between the annual solar heat gain by conventional façade and the corresponding OTTV.

Chapter six presents a general overview of the research. The set-out objectives along with the questions posed in Chapter one is reviewed to present the thesis conclusion and contributions. The Chapter also identify possible directions for future research and recommendation on the study's findings.

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